Response to Referee 2's comments

Below we summarise the comments of Referee 2, along with our responses and actions:

#	Comment (verbatim)	Response	Action
R2.1	"I believe a product such as this, and particularly the associated uncertainties, require a much more detailed treatment than what has presently been done." "I believe that the uncertainties in the data are larger than were presented in the paper due oversimplification of errors as well as the possible exclusion of key uncertainty factors."	There are insufficient observations to fully characterise (i.e. correct for) certain sources of variability in the retrieval of sea ice thickness and volume. Because of this, our estimates of sea ice thickness and volume are in error. Examples include temporal variations in the microwave scattering horizon, spatial variations in snow loading, and temporal variations in the concentration and extent of sea ice. None of these signals have been adequately sampled using independent measurements, and so we cannot be sure of their variance. To account for this, we introduce uncertainties in the key factors of our retrieval based on information present within the published literature. In the case of our archive product, this includes uncertainties in snow depth, snow density, ice density, sea ice concentration, sea ice extent, and sea ice freeboard (which decorrelates rapidly in space)(Tilling et al., 2015). We do not include an uncertainty associated with temporal variations in the microwave scattering horizon (i.e. the difference between the radar and ice freeboard), because these have been shown to rapidly decorrelate with time and to preferentially affect waveform retrackers designed to locate the ice surface (Ricker et al., 2015), which we do not employ. Our error model leads to uncertainties in Arctic-wide sea ice volume of around 15 %, and in sea ice thickness of around 25% at the 25 km scale of our grid. The latter are comparable to the spread of differences between our archive product and independent	We have expanded our error budget to include the contribution of sea ice freeboard uncertainty due to a.) sea surface height uncertainty and b.) floe height measurement uncertainty (due to radar speckle and random noise in the retracking step). Please see our response and action to **R2.3** and **R2.17**. We have added the treatment of a.) and b.) to the description of our error analysis, and introduce these by stating that *"The construction of our error budget is described in Tilling et al. [2015], but we now expand on this by considering the contribution of uncertainty in sea ice freeboard in more detail."* We have been explicit about which other factors we account for and have strengthened our description with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3). We also highlight our desire to further tackle the largest sources of uncertainty, and their associated errors, in our concluding paragraph. The relevant sentence reads: *"The next steps in the advancement of the data are to develop improved estimates of snow loading on Arctic sea ice, and to*

		measurements of sea ice thickness determined from airborne and in situ platforms. Were this not to be the case, we would agree with the assertion that our errors are not well characterised. However, it is, and so we believe that our error budget is in fact a reasonable and credible assessment of the uncertainty in our retrieval. The reviewer does make some specific suggestions as to how our error budget might be modified to suit the case of the near real time data set, which is spatially and temporally under-sampled relative to the archive product. We agree that these suggestions make good sense, and so we have modified our error budget to take these additional uncertainties into account..	*further constrain the uncertainties in snow loading and sea ice density."*
R2.2	"In several areas of the text the mathematical operations performed on the data need to be explicitly written out as otherwise it is unclear exactly how some of the calculations were done. One example on this is that it is unclear whether a correction for the slower speed of light in snow has been applied to the calculation of freeboard. It is stated in Tilling et al., 2015 "A correction is applied to each freeboard measurement to account for the attenuation of the radar pulse as it passes through any snow cover on sea ice, where snow depth is based on a climatology." But this sentence is confusing as it could also apply to attenuation of energy through the snow, which in itself would not necessarily impact the freeboard determination. If this factor is applied, and whether it was	We agree that it is unclear in our original manuscript whether a correction for the slower speed of light in snow has been applied to the calculation of freeboard. We also accept that the use of the word "attenuation" could cause confusion. We agree also that it would be helpful to the reader if the factors included in our error budget were stated more clearly in the text. However, we do not agree that the mathematical operations performed on the data should be written out in full, because they do not differ from those presented in an earlier manuscript (Tilling et al., 2015); the aim of this study is to merely apply our method to fast delivery CryoSat-2 data and compare to archive results.	We have added a sentence to the methods paragraph stating that: *"A correction is applied to each freeboard measurement to account for the reduced speed of the radar pulse as it passes through any snow cover on sea ice."* Should the reader require any further information on our methods we now direct them explicitly to Tilling *et al.* (2015). The second Data and Methods paragraph, first sentence, now reads: *"The processing steps for fast delivery CryoSat-2 data are identical to those used for the final delivery data, and are described in Tilling et al. (2015)."* We have also included a more in-depth description of our error analysis, and strengthened this with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3).

	applied in the determination of sea ice thickness and volume uncertainty, is not clear in the text.”		
R2.3	“It is also unclear how freeboard retrieval errors would propagate into the uncertainty calculations. Tilling et al., 2015 state that an interpolation is done between ocean surface elevation measurements to determine freeboard. The interpolation procedure was not explicitly stated but needs to be done so here. Any such interpolation would change the correlation length of the errors in the assessment and needs to be considered.”	We agree that we should reconsider the contribution of freeboard uncertainty associated with the sparse sampling of the near real time products computed over short time intervals. We do this by comparing sea surface height profiles along individual Arctic passes for crossovers where the time between the ascending and descending arc is sufficiently small that the real sea surface height has not varied significantly (say three days or less). On average, sea surface heights have a standard deviation of ~6 cm. When combined with the difference between the sea surface height of the ascending and descending arc, the total uncertainty on an individual interpolated sea surface height is ~4 cm. We interpolate sea surface heights using along-track linear regression with a moving window of width 200km, so this uncertainty contribution due to sea surface height interpolation will be correlated between freeboard measurements along the same satellite pass separated by 200 km or less. We also agree with the reviewer that we should explicitly state the interpolation procedure.	We now consider the contribution of freeboard uncertainty, due to sea surface height interpolation, to our sea ice thickness error. This is considered separately to the contribution of freeboard uncertainty due to floe height measurement uncertainty, which is caused by radar speckle and random noise in the retracking step. Both of these are explained in detail in the text, with regards to their contribution to uncertainty in sea ice volume (third Data and Methods paragraph) and sea ice thickness (fourth Data and Methods paragraph). The interpolation procedure is now explicitly stated in the text. The relevant sentence reads: *“Sea surface height measurements are interpolated using along-track linear regression with a moving window of width 200km. ”*
R2.4	**P2L25:** “The need for model ingestion is mentioned. But it should be considered that many models which ingest data have trouble with gridded mean sea ice thickness data and prefer to work with swath level data because sea ice thickness in modern models is represented as a distribution rather than a mean value. It	Although we acknowledge that different data formats may be desired by different users, we provide the gridded product as it is compact and evenly distributed, to satisfy a wide range of users. Bespoke products, such as swath level data, are available on request. .	No changes made, because the remark relates to our data product rather than the manuscript.

	would be more useful to provide the point to point measurements of freeboard (the actual measurement made by CryoSat-2) which could be more easily ingested in a model."		
R2.5	**P4:** "The mathematical expression for determination of sea ice thickness error needs to be written out."	We agree that it would be helpful to the reader if we included the mathematical expression for the determination of sea ice thickness error.	We have included a mathematical expression for the conversion of sea ice freeboard to thickness (equation 1) to introduce the processing step at which the uncertainties are introduced. We have also expanded our description of our error analysis, and strengthened this with mathematical expressions for the determination of our errors (equations 2 and 3).
R2.6	**P4:** "Was the uncertainty due to the lower speed of light in snow considered in the error estimates?"	We appreciate that this was not clear from the paper	We have included a more in-depth description of our error analysis, and strengthened this with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3). From this we hope that it is clear that the uncertainty due to the lower speed of light in snow was not considered in our error estimate. However, we have also included explicit reference to this in our concluding paragraph by stating that: *"Our sea ice thickness and volume error budget could be further constrained by improved knowledge regarding the uncertainties in snow loading and sea ice density, as well as accounting for the uncertainty due to the reduced speed of light propagation through the snow pack."*
R2.7	**P4L27:** "The mathematical expression for the circular operator needs to be written out as it is unclear how this was applied to the data."	We agree that we do not make it clear how the circular operator was applied to the data. On consideration, the phrase 'circular operator' is misleading and needs to be removed.	The relevant sentence now reads: *"To obtain Arctic-wide and ROI grid values, we average all thickness measurements within a 25 and 5 km radius of the centre of the grid, respectively, with all points receiving equal weighting."*

			We have also removed the reference to the 'circular operator' in the caption of Figure 1.
R2.8	**P3L19:** "The reference to Kwok et al., 2009 is confusing here as the paper does not describe the use of CryoSat-2 data."	We agree that the reference to Kwok *et al.*, 2009 is confusing, and that we need to clarify how it is relevant to CryoSat-2 data	The sentence now reads: *"NASA provide monthly-averaged thickness data for March 2014 and March 2015 within a fixed central Arctic region that covers an area of ~7.2×10^6 km^2. The region was first defined for use with the NASA ICESat satellite [Kwok et al., 2009], and will herein be referred to as the ICESat domain."*
R2.9	**P4L5:** "Which geophysical corrections are often missing in the data? They should be listed."	We agree that the geophysical corrections should be listed	The sentence has been expanded to read: *"In the fast delivery data the wet tropospheric, dry tropospheric and inverse barometer corrections are missing in 93.8% of cases for Baseline-B data, but only 0.3% of cases for Baseline-C data. In these cases, all three of the corrections are missing. "* We have moved the sentence further up in the paragraph as we feel it makes more sense to include it immediately after the baseline processing is introduced.
R2.10	**P4L16-17:** "How is snow from the Warren climatology applied beyond areas of the central Arctic? The reasons for this were mentioned clearly in the other review. I think this is a critical part of the manuscript as this could have a large impact on first year ice areas outside of the central Arctic basin."	We appreciate the referee's concern regarding the Warren climatology, especially in regions where it is not constrained by *in situ* measurements. To avoid using unconstrained value of snow depth and snow density we use the mean climatology values of snow loading from a fixed central Arctic domain (where snow parameters are constrained) in all freeboard to thickness conversions, no matter where they are located. There are known differences between the climatology and the current snow depth on younger Arctic sea ice (Kurtz *et al*. 2011; Webster *et al*. 2014) so we halve the snow depth on FYI to account for reduced snow accumulation. This should be explicitly stated in the paper.	A sentence has been added to summarise our treatment of the Warren climatology. It reads: "*To obtain snow depth and density we average the values from a climatology (Warren et al. 1999) that fall within the ICESat domain, where the climatology is constrained by in situ measurements*." The ICESat domain is defined earlier in the paper. Should the reader require further information, the second paragraph in the Data and Methods section, first sentence, now reads:

			"The processing steps for fast delivery CryoSat-2 data are identical to those used for the final delivery data, and are described in Tilling et al. (2015)."
R2.11	**P4L17-18:** "The specific densities for sea ice and water need to be written out."	We agree that these densities should be written out	We have added the densities to the paper. The relevant sentence now reads: "We use a fixed estimate of first-year ice (FYI) density of 916.7 kg m^{-3}, multi-year ice (MYI) density of 882 kg m^{-3} [*Alexandrov et al.*, 2010], and a fixed seawater density of 1,023.8 kg m^{-3} [*Wadhams et al.*, 1992]."
R2.12	**P4L26:** "If a 1 km grid can be provided, why not also provide the swath level freeboard data which is of similar resolution?"	We appreciate that some users would prefer to have swath level data. However, this paper is intended as an introduction to the dataset that is currently publicly available. We provide the gridded product as it is compacts and evenly distributed, to satisfy a wide range of users. The 1km data is available over reduced regions of interest, so is still more compact than numerous satellite swaths. Bespoke products, such as swath level data, are available for collaborators on request.	No changes made, because the remark relates to our data product rather than the manuscript.
R2.13	**P4L37:** "Given the extrapolations of the Warren climatology outside of the central Arctic, as well as the modified version over first year ice, I would question these snow depth uncertainty estimates as they have been quite modified from their original source."	We agree with the referee that snow depth has been quite modified from its original source, and that this may cause issues with uncertainty estimates. However, there is a lack of real knowledge regarding the uncertainties in snow depth, as well as snow density, and sea ice density. We have attempted to account for this lack of knowledge in our error budget by including errors of snow depth, snow density and sea ice density that are likely an overestimate, owing to the sparse spatial and temporal sampling of the measurements [*Tilling et al.*, 2015]. We have developed the most comprehensive error budget we can, considering this lack of knowledge. We	We now highlight our desire to tackle this issue in our concluding paragraph. The relevant sentence reads: *"The next steps in the advancement of the data are to develop improved estimates of snow loading on Arctic sea ice, and to further constrain the uncertainties in snow loading and sea ice density."*

		believe that our error budget is a reasonable estimate of uncertainty, as the values are consistent with published comparisons of CryoSat-2 sea ice thickness estimates with independent measurements of thickness and draft from airborne and ocean-based platforms (Tilling *et al.*, 2015).	
R2.14	**P4L42-44:** "The statement that the large number of freeboard measurements negates the uncertainty rests on the assumption that the errors are uncorrelated in space and time. This seems highly unlikely given that the retrieval method does not account for factors such as changing snow conditions as shown by Ricker et al., 2015."	We do not assume that uncertainties in freeboard are uncorrelated in space and time, as the referee suggests. Rather, we have attempted to characterise the degree to which they are correlated using an empirically determined length scale within our error budget. This approach leads to larger uncertainties when compared to error budgets that assume uncorrelated uncertainties (e.g. Ricker *et al.*, 2014). Again, our error model leads to uncertainties in sea ice thickness that are comparable to the spread of differences from independent measurements determined from airborne and in situ platforms, and this leads us to believe that the model is in fact a reasonable and credible assessment of the uncertainty in our retrieval.	No changes made
R2.15	**P5L1-7:** "The method for determining volume uncertainties is unclear and should be written out mathematically to fully describe the procedure. Also, over what range is each parameter adjusted to calculate the rate of change?"	We agree that it would be helpful to include the mathematical expression for the determination of sea ice volume error	We have included a more in-depth description of our error analysis, and strengthened this with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3).

R2.16	**P5 second paragraph:** "I think this estimate of error is a gross simplification of the un- certainties and is not accurate. For the snow depth term, it was already acknowledged that there are large differences over first year and multi-year ice which are unrelated to synoptic scale meteorology but is rather related to the timing of snow fall events and ice freeze-up. Sea ice density would also similarly be unrelated to synoptic scale meteorology particularly as the values used in the study are based on first year and multi-year ice types. I would therefore not consider the 2000 km decorrelation length to be accurate. Have you looked at other data to determine the decorrelation length for these parameters?"	We appreciate the referee's concern that our estimate of error is a simplification. However, there is a lack of real knowledge regarding the uncertainties in snow depth, snow density, and sea ice density. We have attempted to account for this lack of knowledge in our error budget by including errors of snow depth, snow density and sea ice density that are likely an overestimate, owing to the sparse spatial and temporal sampling of the measurements [*Tilling et al.*, 2015]. We have developed the most comprehensive error budget we can considering this lack of knowledge. Our uncertainty estimates are consistent with published comparisons of CryoSat-2 sea ice thickness estimates with independent measurements of thickness and draft from airborne and ocean-based platforms (Tilling *et al.*, 2015). Again, we believe that attempting to characterise a de-correlation length scale is an improvement on alternative error budgets that assume uncorrelated uncertainties.	We have expanded our error budget to include the contribution of sea ice freeboard uncertainty due to a.) sea surface height uncertainty and b.) floe height measurement uncertainty (due to radar speckle and random noise in the retracking step). Please see the response and action to **R2.3** and **R2.17**. We have added the treatment of a.) and b.) to the description of our error analysis, and introduce these by stating that "*The construction of our error budget is described in Tilling et al. [2015], but we now expand on this by considering the contribution of uncertainty in sea ice freeboard in more detail.*" We have been explicit about which other factors we account for and have strengthened our description with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3). We now take care to be completely transparent about the difficulties associated with determining de-correlation lengths for contributing uncertainty factors. We open the fourth Data and Methods paragraph by saying: "*Estimating the error on individual or grid cell sea ice thickness measurements is complicated by lack of knowledge regarding the de-correlation length scales of the contributing uncertainty factors.*"
R2.17	**P5 second paragraph:** "The last sentence in this paragraph not accurate as there is likely residual error in the sea surface	We agree with the referee that it is important to consider how spatial variations in sea surface height references will impact on sea ice thickness uncertainty.	We now consider the impact of spatial variations in sea surface height references (when calculating sea ice freeboard) on sea ice thickness uncertainty. This is

	height estimate since there is a need to interpolate over data gaps due to the varying number of lead points available. The interpolation procedure needs to be written out so that the correlation length of errors in the sea ice thickness can be better understood and taken into account.”	Although uncertainty in sea surface height (~4 cm, see response to **R2.3**) will be a negligible component of our monthly volume uncertainty, as we typically include more than 1 million floe heights and 10,000 200 km arc segments when computing, it will impact on thickness uncertainty as the sea surface height uncertainty will remain correlated along each satellite pass crossing a 25 km radius averaging window. We estimate that the effect will be reduced in the averaging only by the square root of the number of individual passes crossing a significant part of the averaging window. Therefore the impact of sea surface height uncertainty on the overall thickness error budget will have a greater impact on thickness for shorter timescales and at lower latitudes, due to the increased sparsity in spatial sampling. We also agree that the interpolation procedure needs to be written out.	described in detail in the text (fourth Data and Methods paragraph). We explain that the magnitude of the contribution of sea surface height uncertainty to our thickness error budget depends on the spatial sampling of the data. We back this up by including typical values for the total thickness uncertainty for varying degrees of data coverage. The interpolation procedure is now written out in the text. The relevant sentence reads: “*Sea surface height measurements are interpolated using along-track linear regression with a moving window of width 200km.”* We now take great care to be completely transparent about the difficulties associated with determining de-correlation lengths for contributing uncertainty factors. We open the fourth Data and Methods paragraph by saying: “*Estimating the error on individual or grid cell sea ice thickness measurements is complicated by lack of knowledge regarding the de-correlation length scales of the contributing uncertainty factors.”*
R2.18	**Figure 2a:** “There appear to be negative ice thickness values in the distribution, I’m guessing this is due to uncertainties in the freeboard retrieval but some explanation on this is in order.”	The referee is correct that negative ice thickness values are due to uncertainties in the freeboard retrieval. We agree that some explanation is necessary.	We have added a sentence that reads: “*The negative thickness values apparent in Figures 2a and 2b are a consequence of negative freeboard measurements that occur due to random noise in the returns from thin ice floes, caused by radar speckle. These freeboards are included in our processing to ensure that the average freeboard, and therefore thickness, is not biased high.”*
R2.19	**“**A map of the differences with the final data compared to the NRT also needs to be shown. This will reveal whether	We understand that readers may desire more information with regards to the spatial differences between NRT and archive sea ice thickness products.	We have included a new figure (Figure 3), which consists of 2 maps, detailing the spatial differences between NRT and archive sea ice thickness data for absent and present

	regional differences are present."	Since our initial submission we have found that the absence of certain geophysical corrections (wet tropospheric, dry tropospheric and inverse barometer), caused the most noticeable differences in NRT and archive sea ice thickness. We feel that the best way to display this is by plotting the spatial variability of these differences for two different months: one with corrections absent and one with corrections present.	geophysical corrections. The explanatory text for this figure (Data and Methods final paragraph, final few sentences) reads: "*The remaining difference is likely due to the combined absence of the wet tropospheric, dry tropospheric and inverse barometer corrections in 93.8% of the Baseline-B fast delivery CryoSat-2 data. This is reduced to 0.3% for Baseline-C data. The mean sea ice thickness for both the NRT and archive datasets is ~1.8 m, and there is no bias between them, with or without geophysical corrections applied. When the corrections are missing the NRT and archive thickness values at any given location differ, on average, by 1.1 cm with a standard deviation of 23.0 cm (Figure 3a). This is reduced to 0.1 cm with a standard deviation of 7.4 cm when the corrections are present (Figure 3b). There is no spatial pattern to these differences. Despite the improvement in performance of Baseline-C NRT data compared with Baseline-B we conclude that the satellite orbits and on-ground processing applied to fast delivery CryoSat-2 data are sufficient to determine accurate measurements of Arctic sea ice thickness and volume for both baselines. The thickness differences between the archive and NRT data products are not significant for either baseline given the estimated uncertainty on thickness and the typical thickness of sea ice floes.*"

References

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